DRAINAGE MODIFICATIONS AND THEIR INTERPRETATION.[1]

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PART I. PRINCIPLES OF DRAINAGE MODIFICATION.

(1) RELATION OF DRAINAGE FORMS TO LAND FORMS.

THE great advancement in the interpretations of physiographic forms which has marked the last decade has led to a better understanding of the late geologic history of certain continental areas than has ever been attained from the study of the sediments deposited around their margin. Although such important results have been derived from this study in so short a time, they are but scattering chapters in the complex history of continental development, and much yet remains to be done before a clear insight can be obtained into the various conditions of the past. Our success in reading this history lies in following out all of the lines of corroborative evidence available, in the hope that where the evidence along any one line is weak, that along another may be strong and complete, enabling us to build up a more or less perfect whole from the different classes of facts.

The process of erosion, according to Gilbert,[1] consists of three parts: weathering, transportation, and corrasion; and is modified by three conditions: declivity, character of rock, and climate. Physiographic forms resulting from the process of erosion are necessarily modified by any change in the above mentioned causes and conditions. But since streams are the principal agents in transportation and corrasion; and since transportation and corrasion are dependent upon weathering (which is modified by climate), declivity, and character of rock, it follows that any change in the causes or conditions affecting erosion will modify the action of the streams and any modification of the action of the streams will tend to change their alignment in accordance with the changed conditions.

This intimate relation between stream alignment and physiographic forms suggests the advisability of thorough study of drainage systems, in the hope of finding some record of past conditions which will throw additional light on the question of the physiographic history of continental areas.

[1] Geology of the Henry Mountains.

(2) CLASSES OF DRAINAGE ADJUSTMENTS.

Neglecting the catastrophic effects of glaciation and volcanic action, drainage modifications may be divided into three classes: (1) Changes marking the progress of a river through a normal cycle of development. (2) Adjustments due to character of rocks and geologic structure. (3) Rearrangements caused by local uplifts or depressions of the earth's crust.

Class 1. Changes during the normal development of a stream.— The modifications falling within this class are well understood, having been thoroughly worked out by Davis and others, but for the sake of clearness will be briefly restated.

A cycle in river development, according to Davis,[1] consists of the interval of time during which a river reduces the land within its watershed to baselevel. Let us for a moment glance at the process by which this is accomplished. In its youth the grade of the stream is necessarily great, since the surface of the land must be far above baselevel. With a steep gradient the current is everywhere rapid, and all of the refuse worn from the land by weathering and corrasion is carried by the force of the current into the sea. The stream so loaded becomes an abrading instrument of great power, and its channel soon partakes of the character of a rocky gorge or canyon. That portion of its course which is nearest the mouth of the stream will first be reduced approximately to the baselevel of erosion. As soon as that is accomplished the gradient becomes so low that the stream can no longer carry its burden of waste to the sea. A portion of its load will be dropped in the channel deflecting the current from its original course and causing it to cut away its banks on the side toward which the current sets. As the current is lessened by these meanders, its carrying power is diminished and it is forced to give up more of its load which is added to the barrier already existing and which tends continually to deflect the stream into broader and broader meanders. Thus in progressing from youth to old age, the stream changes its appearance in accordance with the changed conditions which surround it. Conse-

[1] The Rivers and Valleys of Pennsylvania, Nat'l. Geog. Mag., Vol. I, p. 203.

quently the history of this portion of the cycle is recorded, not alone in the sculptured forms of the land, but also in the changed alignment of the streams.

As the stream approaches extreme old age, its gradient grows less and less, and the divides between adjacent streams become so low that many adjustments are required before a perfect balance prevails between the contending streams. This is due to the fact that in this portion of the cycle the streams are but slightly prepared to defend themselves, and any stream handicapped by a circuitous route to the sea will eventually suffer loss of drainage area at the hands of a neighboring stream.

It would be almost impossible to read the history of drainage developments, unless we could go back for our beginning to some period in which drainage conditions are known. During its period of youthful development, a stream leaves but few traces by which, in after years, we may judge of the extent of its drainage basin, or of the conditions under which it labored; during its maturity its records are equally unintelligible, for they tell us nothing of the local conditions which surrounded it; but in its old age we can say with confidence that, so far as it is untrammeled by local obstacles (and local obstacles are rare in this stage of erosion), it is evenly balanced against the surrounding streams. If then we find traces of a stream having reached old age, we can calculate with reasonable certainty the extent of its basin, or if its basin does not extend to the limit which should mark the contending streams, we may be assured that local obstacles interfered with its normal development. Thus the last stage of the life history of a river implies certain physical conditions, consequently it is the period to which we must refer in undertaking to read the history of drainage developments.

Class 2. Adjustments due to rock character and geologic structure. —Drainage modifications which fall within this class have received the attention of our ablest physiographers, hence their mode of origin is well understood. Gilbert has shown how streams, flowing on inclined beds of alternating hard and soft

rock, will naturally tend to migrate down the slope of the beds, producing a change in the alignment of the streams. Davis has fully demonstrated that streams flowing over folded and faulted rocks will first have their positions determined by the synclinal folds of the structural surface, and then they will migrate to the anticlines, or in technical terms will change from consequent to subsequent streams.

Changes due to these conditions are of great importance in drainage studies, but, since complicated geologic structure is limited to small areas compared with the continental mass, such conditions can prevail only in a prescribed area, and consequently affect but a limited number of streams. Hence in a general study of drainage changes, this class does not deserve the prominence that has been attached to it.

Class 3. Rearrangements caused by radial crustal movements.— If the earth's crust remained entirely free from movement, the history of the drainage would be extremely simple, consisting of but a single cycle; and its barrenness of striking features would only be equaled by the monotonous expanse of baseleveled plain which would be produced during the cycle. The present diversity of surface features is positive evidence that such has not been the case—that the crust of the earth has suffered repeated oscillations which have prevented the formation of such an extensive baseleveled plain, and at the same time have complicated the drainage history to a remarkable extent.

Recent studies of the Mesozoic and Cenozoic peneplains of the southern Appalachians seem to demonstrate that this region has suffered two kinds of crustal movements in post-Palæozoic time. Both of these come under the class of radial movements, but they differ in the intensity of the deformation of the baselevel and in their lateral extent. For convenience of study we may divide them into general and local oscillations. As the name implies, the first class embraces those movements of elevation or depression which are of continental or semi-continental extent. Since the amount of movement is slight compared with the horizontal extent, the deformation will be so slight as to be

unrecognizable. These movements may produce a complete transformation of the drainage features of a land area by causing a portion of it to be depressed below drainage level; or they may cause the revival, or rejuvenation of the streams by lifting the land above its previous position. In any case the modifications arising from such movements will fall under the first class, or those due to the natural course of events in a normal cycle of development.

Crustal movements of the second, or local class affect but a limited area. They consist of uplifts or depressions which reach a maximum along an axial line, grading off to the undisturbed strata at no great distance on either side. The local movements which have occurred in the past have not generally been intense enough to cause a perceptible dip of the rocks, but they have elevated the surface into broad ridges, or depressed it into shallow troughs.

The effects of these local movements upon the drainage must have been very different from the general movements. They would cause no general revival, but would affect the streams locally, and consequently their effect in producing rearrangement must have been very much more potent. The principal object of this paper is to study the effect of these local movements upon the streams; to endeavor to establish the criteria by which the changes due to this influence may be recognized; and lastly to apply these criteria to a continental area, and by their assistance endeavor to read the history of the region in question.

(3) IDEAL CASES ILLUSTRATING THE EFFECT OF LOCAL EARTH MOVEMENTS.

In studying this subject in the field, the observer is frequently confused by local conditions of geologic structure and alternation of hard and soft strata, which apparently overshadow the more subtle influence of crustal warpings; although the latter may, in a general way, be the dominating force which has shaped the drainage systems. In a theoretical consideration of

the question, however, we can eliminate the local disturbing conditions and thus determine the true value of surface warpings as stream modifiers.

We will then assume a land area in which the strata are horizontal and perfectly homogeneous and, for farther simplification, will suppose that its surface has a regular descent from a low, interior water-parting toward the sea on either side. If in such an area the climatic conditions are the same on either side of the dividing ridge, the rate of erosion would be the same and the opposing streams would be held in a delicate balance against each other. The amount of energy expended by one stream in corrading its channel would necessarily be the same as that of its antagonist and the gradient of the streams, in their various portions, would show a close correspondence.

(*a*) *Effects of elevation.*—If then an uplift should occur across one stream a short distance from the divide, it would not materially change the ratio of energy expended by the streams in the corrasion of their channels; each would be increased by the increased gradient, but the energies would be expended in very different portions of the channels. The stream which is not crossed by the axis of uplift would have its gradient near headwaters increased, and consequently the greater portion of its corrasive energy would be concentrated upon the divide at its head. The stream which is crossed by the axial line would have its gradient near headwaters diminished, while below that line its gradient would be increased, consequently a large amount of its energy would be transferred to that part of its course which is below the axis of uplift, and almost none would be used on the divide against which its antagonist is concentrating all of its force. There can be only one result, and that is the gradual eating away of the divide on the side opposite the uplift, and the consequent migration of this divide toward the axis of elevation. It matters not how slow nor how slight is this uplift, its effect will be the same in character, though differing in amount of modification produced. The principle is fundamental and must apply in all cases.

Figures I to 4 are a graphic representation of the manner in which such an uplift would affect the drainage and cause the divide to migrate towards its axis. Let *A*, *E* (Fig. I) represent a

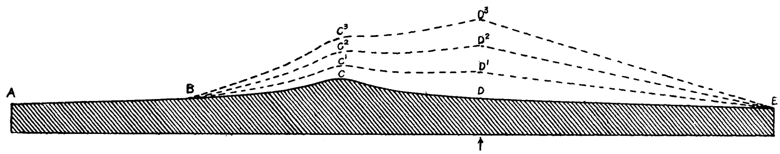

FIG. I.

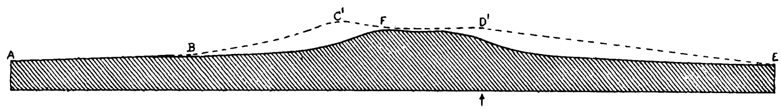

FIG. 2.

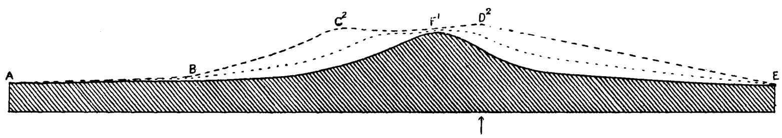

FIG. 3.

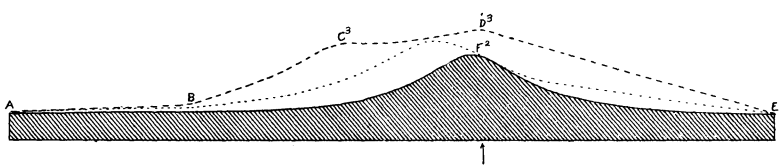

FIG. 4.

cross-section through the divide *C* separating two streams flowing in opposite directions, the profiles of which are represented by the curved lines *A*, *B*, *C* and *E*, *D*, *C*. Let us suppose still farther that the streams are balanced against each other, consequently the profile will be symmetrical. It is evident that the divide *C* will remain stationary unless some external cause interferes to disturb the delicate balance now maintained. Suppose that such an external cause elevates the strata at the point *D*. Since we are dealing with the effect of local movements, we will suppose that this movement extends each way only so far as the points *E* and *B*. Now if the point *D* were elevated by the force

represented by the arrow, it would take successively the positions D^1, D^2, and D^3, and the divide C, if it remain stationary, would occupy the positions C^1, C^2 and C^3. If the movement were sufficiently rapid, so that erosion produced no sensible effect, it is obvious that when the point D reached D^3, it would be at a greater altitude than C^3, and consequently the divide would be shifted from C to D; thus the stream flowing toward E would be beheaded and the stream flowing toward A would be increased by the beheaded portion.

It is not at all probable that the great majority of crustal movements are rapid enough to produce this effect. Let us examine the problem and see if a slower rate of elevation would affect the drainage.

Suppose that the rate of elevation is but little more than the rate of erosion. Under the supposition the condition of the divide would be represented approximately by Figs. 2, 3, and 4. Generally the first result of the uplift is the formation of a barrier at the point D, but if the rate of movement is very slow and the rocks soft, the stream may cut away this barrier as fast as it is produced by the upward movement. The rising of the land and the cutting of the stream continue until the elevation reaches D^1; at that period of development the condition of the streams and the divides is shown in Fig. 2. The original surface is represented by the broken line, A, B, C^1, D^1, E. According to our assumption, the streams were nicely balanced against each other before the uplift occurred, hence the slightest elevation at D would raise a barrier in the pathway of the stream C, D, E, and while this stream may be able to remove the barrier, it involves a certain expenditure of time and energy which the stream A, B, C, is not required to make. Thus the effect of such a barrier is to retard the stream which it crosses, but in the case under consideration the uplift not only retards one stream, but it steepens the grade of the other and consequently accelerates its corrasive power near headwaters.

Under such favorable conditions, it would cut rapidly into the divide at C while the other stream is expending its energy in

keeping its channel free at the point *D*. The actual amount of corrasion accomplished by the two streams is probably not far from the same. The stream *A*, *B*, *C*, is accelerated greatly, but this acceleration is limited to its headwaters where its volume of water is small, hence its power of corrasion is not proportionately increased: on the other hand the stream *E*, *D*, *C*, is retarded at its headwaters, but accelerated in its lower course, and since its volume of water is greater at the point of acceleration, its power of corrasion is considerably increased, although its gradient is but slightly changed. This transfer of active corrasion from *C* to *D* is what weakens the stream *E*, *D*, *C*, and gives the stream *A*, *B*, *C*, its great advantage; for nearly all of the cutting of the latter stream is confined to the immediate vicinity of the gap. When the point *D* is elevated to D^1 the profile of the streams will be *A*, *B*, *F*, *E*, instead of *A*, *B*, *C*, *D*, *E*, and the divide will have migrated from *C* to *F*.

This process is continued as the point *D* is elevated. When it reaches D^2 (Fig. 3) the stream *E*, *F* will have been so handicapped by the uplift across its course and the stream *A*, *B*, *F*, so accelerated by the same movement that the divide will have migrated still further toward the axis of uplift and will occupy some such position as F^1. Again the uplift continues and the point *D* reaches D^3, and the divide F^1 reaches the position F^2.

The figures (1 to 4) would seem to indicate that the rate of migration is the same for a given amount of elevation whether the divide is near or far from the axis of uplift. Such can hardly be the case, for if the axis crosses the stream at some distance from its source it will be at a point where the gradient of the channel is less than if the axis were near the headwaters of the stream; consequently the stream which is retarded will suffer most at the first uplift and as a consequence the divide will tend to migrate rapidly. Later uplifts will occur at points where the gradient is steep and consequently they will have but little effect. In the case of the stream which is accelerated, the tendency will be different. At the beginning of the uplift the drainage basin is so far removed from the axis of the uplift that

its effects are somewhat feeble; but as the divide migrates toward the axial line the acceleration of the stream will become greater and its most effective work will be accomplished when the divide approaches close to the axis of elevation. In balancing the two processes, it seems probable that the former is the controlling element and that the divide migrates more and more slowly as it approaches the axis; and the duration of the last stage may be many times that of the first.

If the uplift continues indefinitely the divide will certainly reach the axis and there it will remain so long as the uplift continues, unless some more potent force causes it to change.

Under the last assumption the rate of the uplift is, at least, equal to the rate of corrasion. We must now consider the case when it is much less. This probably approaches more nearly the actual condition which has accompanied each movement in this province. Since the rate of elevation is less than that of corrasion, the streams can more than keep pace with the rising fold, and hence their profiles will change only in a nearer approach to baselevel and the migration of the divide toward the axis of uplift. The conditions remain practically the same as in the previous case, except that now the divides will migrate more slowly and will constantly approach baselevel.

If the axis of uplift corresponds with the original divide (Fig. 1), there will be no migration, for each stream will be accelerated equally, and each will concentrate its energies at the same point — the divide *C*. The position of the divide *C* will be maintained as long as the uplift continues, unless some external cause exerts a more powerful influence in an opposing direction.

(*b*) *Effects of depression.*— As we have already seen, any pronounced tilting of the surface of the earth tends to produce a migration of the divides in the region affected by the tilt, hence the principle of the migration of divides will apply equally well whether the movement be elevation or depression. And while in the great majority of cases of earth movements the effect is to elevate the land, there are well-marked cases of local

subsidences in the Appalachian province ; and it is well to consider the case in detail so as to familiarize ourselves with the phenomena which it produces.

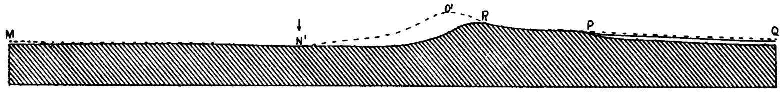

FIG. 5.

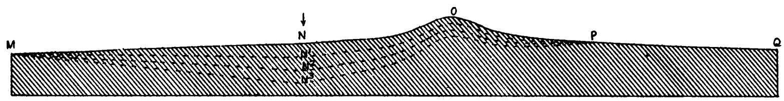

FIG. 6.

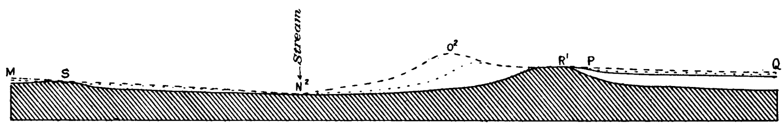

FIG. 7.

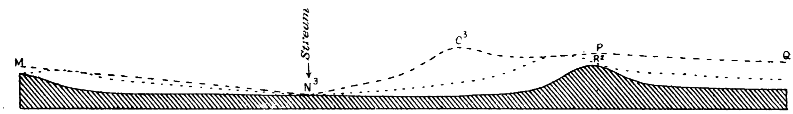

FIG. 8.

Starting with the assumption of two streams, *M*, *N*, *O* and *Q*, *P*, *O* (Fig. 5), equally balanced against each other, we will suppose a subsidence to occur at the point *N*, causing it to assume in successive order the position N^1, N^2 and N^3. It is obvious that if the depression is more rapid than the corrasion of the stream on either side of the depression, the stream will become ponded at the point *N*, and will, in all probability, seek an outlet at right angles to its former course and approximately along the axis of subsidence. If, on the other hand, the movement is so slow that erosion can keep pace with the depression the change will not be so radical, but in the end will result in approximately the same arrangement as sketched for the former case. It will be accomplished about as follows: In the first stage of the

movement, when N is depressed to N^1, the stream M, N, O will have been seriously retarded by the decreased gradient of that portion of its upper course which is within the limits of the crustal movement. In this first stage, as shown by Fig. 6, the stream has lost almost all of its gradient, and corrasion along the lower course of the stream has not been able to relieve the sluggish portion of its upper course. It is incorrect to consider the entire upper course as retarded; the portion below the axis of depression, or that portion which is tilted toward the head of the stream, is rendered sluggish; but that portion which is above the axis is considerably accelerated by the downward tilting and the stream will corrade its channel back into the former divide. The stream Q, P, O will suffer by the depression of its headwaters, and so will be deprived of the power to hold its own against the opposing stream. As in the cases already discussed this divide will migrate toward the weaker stream, or away from the axis of depression.

If the subsidence continues, the point N will soon be lower than the stream channel farther down, and consequently ponding will ensue, until the ponding waters can find an outlet in some other direction. This is supposed to have occurred in Fig. 7, and a transverse stream is located at the point where the axis crosses the course of the former stream. A new divide is thus formed between M and N, its position depending upon the readiness with which the waters find an outlet at N. On the other hand, the divide R will have migrated to R^1. In the last stage the divide S will have reached M and the divide R^1 reached R^2.

In comparing the results obtained when the movement is depression with those produced by elevation, it will be found that the changes are of the same character whether the movement is elevation or depression, or whether it is fast or slow. In all cases the divides will tend to migrate up the slope of the tilted surface, and they will so continue until the point is reached where the surface is unaffected, or else is inclined in another direction.

In the cases so far considered we have assumed that the process continues to its completion—that the uplift or depression was of such duration that the streams became perfectly adjusted to their changed conditions, and that the divides in all cases reached the highest point on the tilted surface. This is the ideal condition, but in reality it is probable that the movements were seldom of sufficient duration to produce this result. Hence in applying these principles in the field we must expect to find cases where the migration was but partial and the streams continue to head across the former axis of uplift. Also we have, in the foregoing cases, assumed the simplest conditions possible. Nowhere in actual practice will the physiographer have to deal with so simple a case as we have here assumed; he will find instead of homogeneous rocks a mass of alternating sandstone, shale and limestone which will greatly modify the results, and he will find complex geologic structure instead of the horizontal rocks in the ideal case. While the actual conditions in the field seem so different from those which we have assumed, the determination of the ideal case furnishes us with a law which applies to all cases, but under complex conditions its results are difficult to distinguish from those produced by other forces.

(4) LAW OF THE MIGRATION OF DIVIDES.

Whenever local radial movements occur in any region the stream divides in that area will tend to migrate; the direction in which they move will be determined by the character of the crustal movement; and the extent of the migration will depend upon the amount of movement and the local obstacles which the streams may encounter. If the movement is upward the divide will tend to migrate toward the axis of uplift; and if the movement continues long enough, and other conditions are favorable, it will reach the axial line and there remain. If the axis coincides with a divide already established it will hold the latter stationary, unless some stronger influence causes it to migrate.

If the movement is one of subsidence the divide will tend

to migrate away from its axis; and will continue in that direction until the streams attain a condition of equilibrium.

The migration of the divide away from the axis of depression generally results in the formation of a stream along the axial line; and the direction in which it flows will depend, in a great measure, upon the pitch of the axis of the fold.

Such is the law of the migration of divides, under the influence of surface warpings. It is probable that if such migrations have occurred in the past we can find some trace of the modifications thus produced and be able to determine the character, direction and extent of the movements, and from that form some idea of the physical condition of the continent in late periods of geologic history.[1]

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U. S. GEOLOGICAL SURVEY.

[1] To be followed by Part II, Criteria for Determining Stream Modifications.